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EXCITATION AND ANALYSIS TECHNIQUE FOR FLIGHT FLUTTER TESTS.(U)
JAN 79 G HAIDL, M STEININGER

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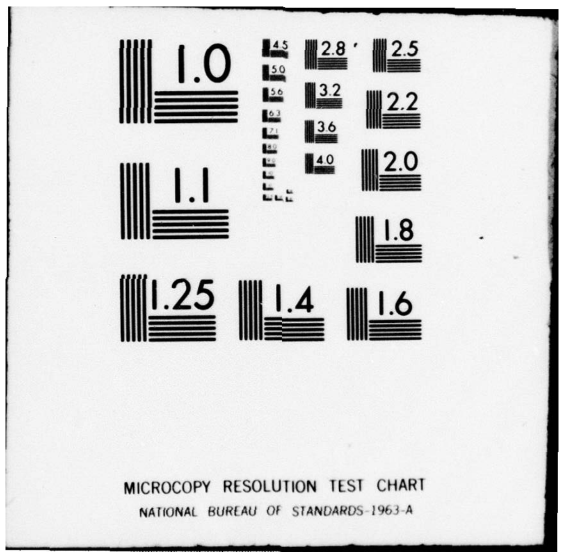
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AGARD REPORT No. 672

Excitation and Analysis Technique for Flight Flutter Tests

by

G.Haidl and M.Steininger

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No. 672

(6) EXCITATION AND ANALYSIS TECHNIQUE FOR

FLIGHT FLUTTER TESTS

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(10) G. Haidl and M. Steininger

(11) Jan 79 (12) 33p.

Paper presented at the 47th Structures and Materials Panel Meeting, Florence, Italy, September 1978

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Published January 1979

ISBN 92-835-1309-6

Printed by Technical Editing and Reproduction Ltd
Harford House, 7–9 Charlotte St., London, W1P 1HD

PREFACE

Extending the flight domain of a prototype aircraft has always been one of the most critical tasks of the aeroelastician. Techniques of excitation and data reduction continually progress but "know-how" still remains decisive.

The paper presented by Haidl and Steininger to the Sub-Committee on Aeroelasticity, at the 47th Meeting of the Structures and Materials Panel, gives a survey of the tools now available for both excitation and analysis. Old, as well as new techniques are described in detail and attention is paid to the difficulties and shortcomings of the different methods.

Consequently, this Report must be considered as a useful guide for all those in the NATO community who are responsible for flight flutter testing.

G. COUPRY
Chairman, Sub-Committee
on Aeroelasticity

CONTENTS

EXCITATION AND ANALYSIS TECHNIQUE FOR FLIGHT FLUTTER TESTS

by

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1. INTRODUCTION

The determination of frequency and damping of vibration modes during flutter model tests or full scale flight tests and the extrapolation of these data plotted versus speed and Mach number is the commonly used method to ensure safe flight envelope extension of new aircraft configurations, to provide correlation with analytical investigations or to actually define critical flutter boundaries.

Since flutter is a potentially dangerous aeroelastic instability, which can lead to catastrophic structural failures or destructions, the flutter safety is strongly dependent upon how good a predicted or unexpected approach to a critical speed will be indicated by damping extrapolation to the next higher test speed for all such modes, which are contributing to a potential flutter mechanism.

The accuracy of analytical prediction and the nature of a predicted potential flutter dictates the effort in this task. All this has to be considered when excitation- and instrumentation-system, test procedure and analysis technique is specified. Test experience indicates the importance of good excitation together with sufficient instrumentation to overcome the mode separation and noise problems in the analysis.

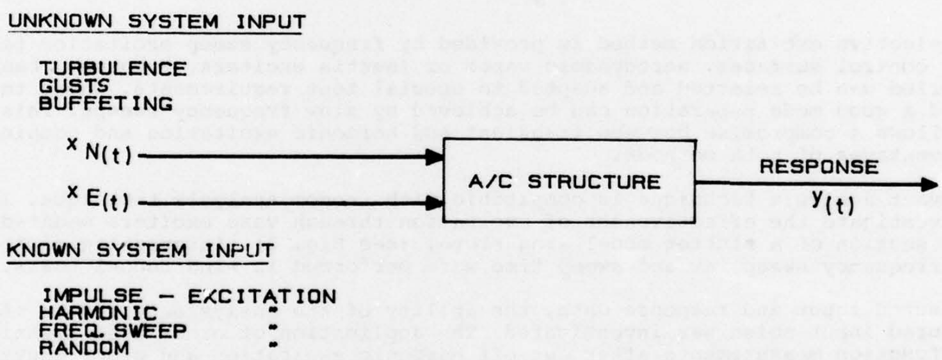

FIG. 1 EXCITATION AND STRUCTURAL RESPONSE

Fig. 1 indicates the excitation inputs to the aircraft, which can be specified as an unknown and a known artificial input.

To provide high quality response data under such conditions an appropriate excitation through control surfaces or vanes is essential.

For example symmetric and antisymmetric excitation, choice of location and sensitivity direction of pickups and positive or negative superposition of relevant signals is often helpful in mode separation and identification.

Most recent developments in test techniques became possible by digital data processing and computer controlled data reduction. A broad and informative survey of test- and analysis-technique is available in the literature showing the efforts in this field. Major problems arise due to the following

- unknown noise input
- short test time available
- necessity of analysis and data interpretation before test continuation
- separation of closely spaced modes
- errors introduced by the analysis procedure.

Atmospheric turbulence and buffet degrades the response data from all types of deterministic excitation, except for random or random like excitation. Thus suitable random response analysis methods based on statistical concepts are required to cope with actual response data. The nonstationary nature of the flight environment, however, and the short time for the test runs lead to new limitations in statistical accuracy. Therefore not only the analysis technique but also the basic assumptions of these methods have to be considered and also how they are fulfilled in real test environment.

These limitations must be taken into account together with computer- or program-specific errors like finite signal length, discrete sampling and effects of periodicity in calculation and in test signals. Systematic investigations may help to get an engineering judgement in the practical application of these techniques under representative conditions.

Common "Off-Line"-analysis techniques can be complemented by computer performed quicklook-analysis, which is important in respect to subsequent test continuation during wind tunnel- or flight tests.

Beside these subcritical test procedures there are interesting developments going on with "active control technology". Closed loop control systems are able to provide artificial damping as well as automatic flutter excitation below and above the flutter speed [5 , 6].

2. EXCITATION AND INSTRUMENTATION IN FLUTTER TESTS

One of the important tasks in flutter testing and subsequent data analysis is to reach an adequate aircraft excitation for all vibration modes of interest.

Transient excitation generated by manually or electrically controlled stick jerks, impulsive cartridges or other devices has the merit of short duration. However, this shifts the mode separation problems mainly to the analysis.

A more selective excitation method is provided by frequency sweep excitation technique using control surfaces, aerodynamic vanes or inertia exciters. Frequency band and time period can be selected and adapted to special test requirements. Short test duration and a good mode separation can be achieved by slow frequency sweeps. This technique allows a compromise between transient and harmonic excitation and combines the main advantages of both methods.

The relevant analysis technique is compatible with random analysis technique. In order to investigate the effectiveness of excitation through vane exciters mounted on the forward section of a flutter model wing store, (see Fig. 2), interesting parameter studies of frequency sweep law and sweep time were performed in wind tunnel tests.

With measured input and response data, the ability of the analysis to reduce effects of not measured input noise was investigated. The application of other test techniques like decay function measurements after cut off harmonic excitation and other conventional methods gave the basis for evaluation of the analyzed frequency and damping trends.

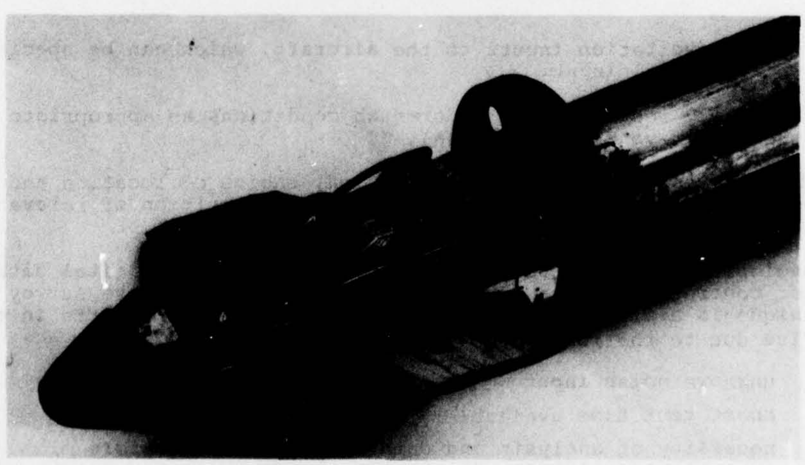

FIG. 2 VANES ON MODEL WING TANK DRIVEN BY ELECTRIC TORQUE MOTORS

The vane exciters on the model tank were driven by electrical torque motors up to $\pm$ 15° deflection angle and a frequency up to about 25 Hz. Frequency and amplitude could be controlled outside the wind tunnel.

Time histories of model responses to frequency sweep excitation going from 3 Hz to 30 Hz and 3 Hz with different sweep duration (20, 40 and 100 sec. up and down) show the effectiveness of the excitation, Fig. 3. The signal beating is due to closely spaced modes wing bending, 6.7 Hz, and store pitch, 7.6 Hz. With shorter sweep duration and long response decay-time problems of superposition are indicated.

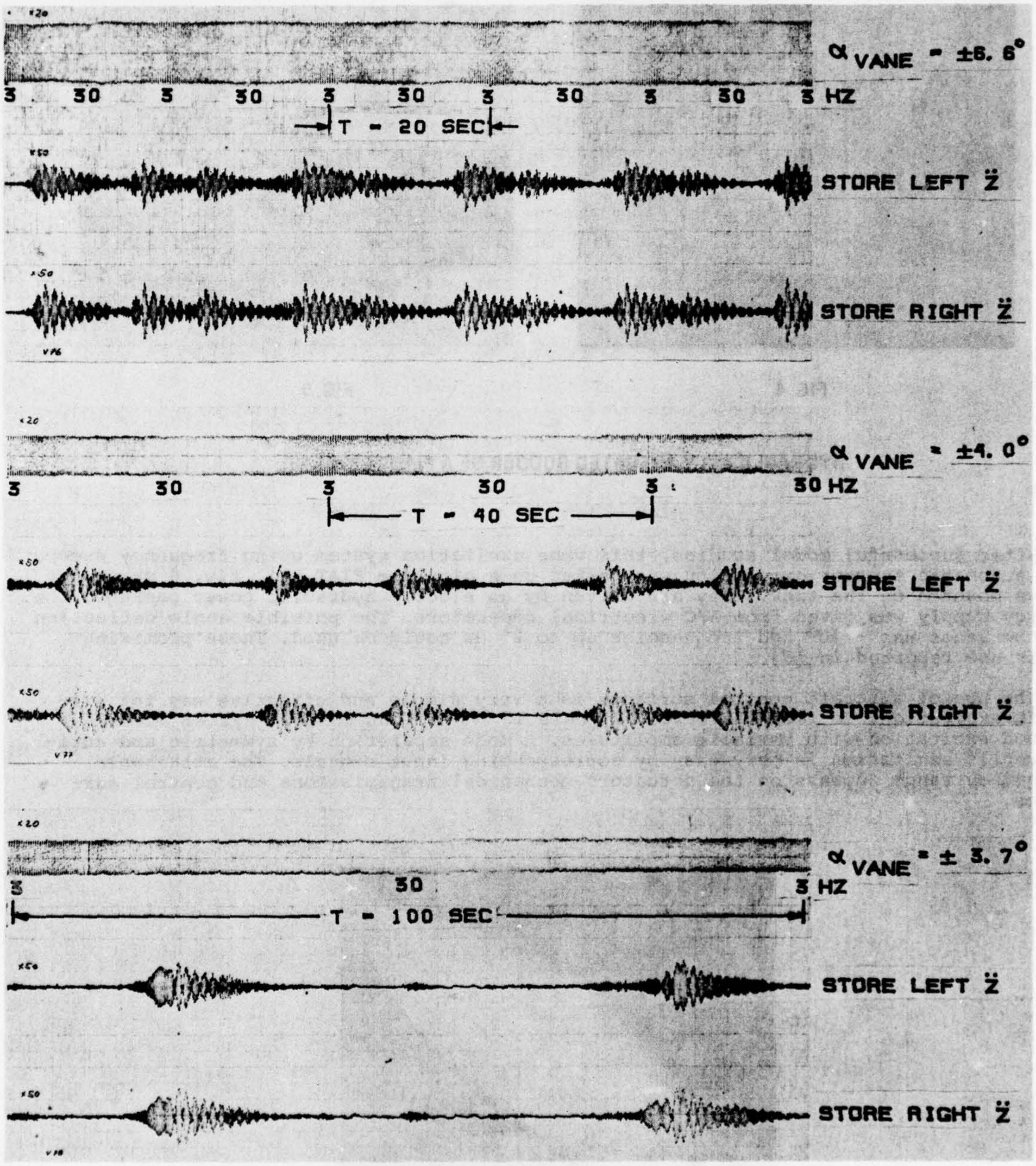

FIG. 3 RESPONSES OF FREQUENCY SWEEP EXCITATION WITH DIFFERENT SWEEP DURATION

In a next step this system together with appropriate sensors in the tank and with a control system was used for automatic flutter suppression and excitation as described in [5]. The technique and results of automatic excitation are treated in section 7.

Similar investigations of excitation technique and active flutter control were performed in a flutter model test series with hydraulically driven rudder actuator up to a rudder angle of $\pm$ 8° and frequency up to 30 Hz. The excitation system with mini-actuators is visible in Fig. 4 and 5.

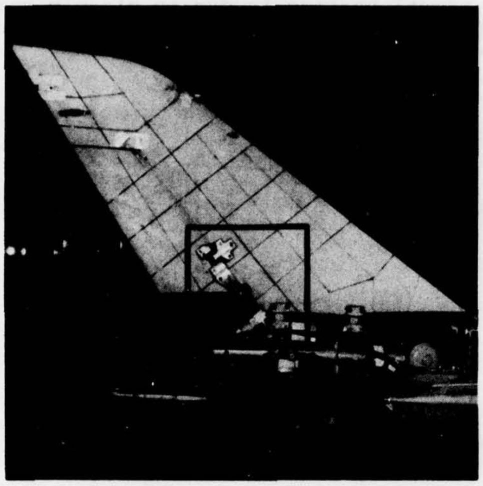

FIG. 4

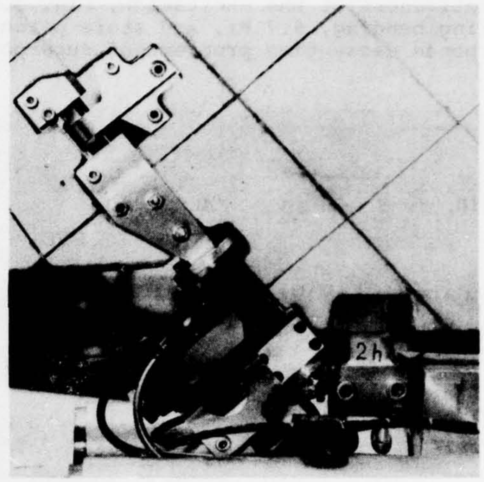

FIG. 5

HYDRAULICALLY ACTUATED RUDDER OF A FLUTTER MODEL

After successful model studies, this vane excitation system using frequency sweep and automatic flutter excitation was tested on a airplane FIAT G91. Fig. 6 shows the vanes mounted on the tank. They are driven by an electro hydraulic power package. The energy supply was given from A/C electrical generators. The possible angle deflection of the vanes was $\pm$ 10° and frequencies up to 25 Hz could be used. These promising tests are reported in [6].

The use of aircraft control surfaces is a very simple and effective way for aircraft excitation. To feed electrical signals in the flight control system allows a good excitation with variable amplitudes. A mode separation by symmetric and antisymmetric excitation is very easy by corresponding input signals. The attainable frequency range depends on the actuators' mechanical transmissions and control surfaces.

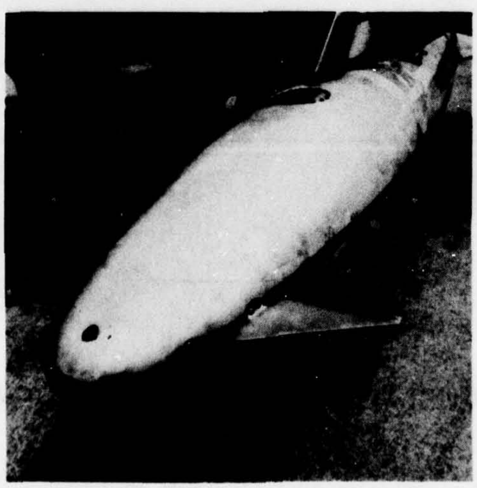

FIG. 6 FLUTTER TANK WITH VANES ON AIRPLANE G 91

Good test experience was gained using this method on the tailerons of A/C TORNADO. The fast actuators of the tailerons allowed frequency sweeps up to 30 Hz in order to investigate tail- and fuselage-vibration modes. Initial trials with only natural turbulence excitation led to misleading damping results as will be discussed later.

Fig. 7 shows an example of aileron excitation applied on an A/C F-4F. Frequency sweeps up to about 10 Hz were used to investigate a new wing-store configuration. Analytical predictions indicated a classical wing bending/store pitch flutter case with low flutter speed.

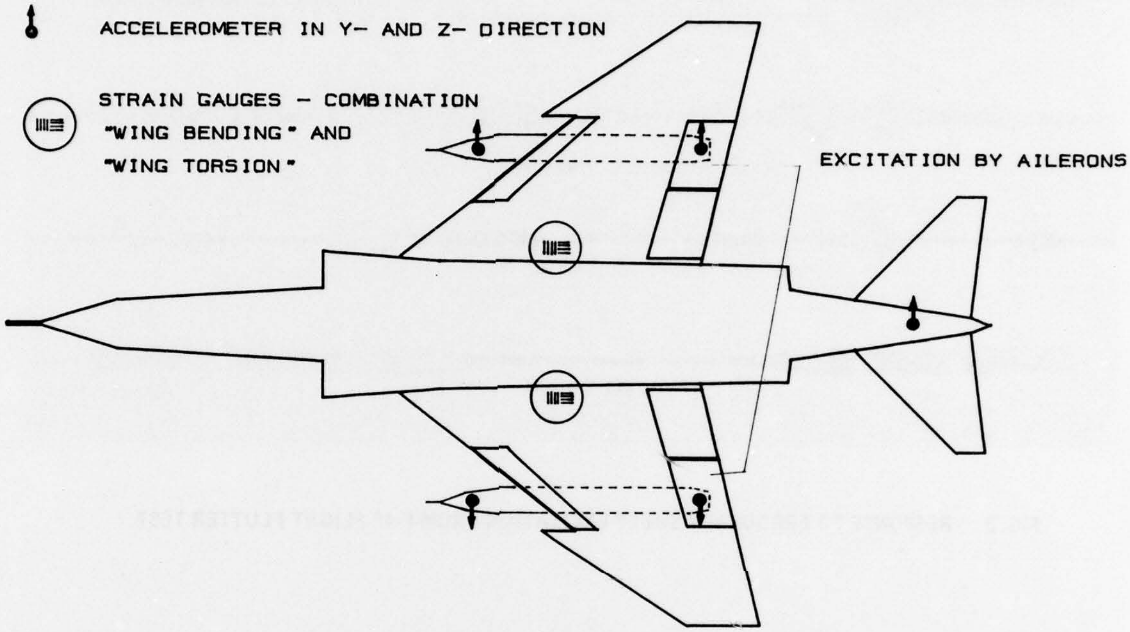

FIG. 7 EXCITER- AND PICK UP INSTALLATION ON AIRPLANE F-4F WITH OUTBOARD PYLON STORES

Even with modified actuators the deflections of the large ailerons were limited to about $\pm 1^{\circ}$ at low frequencies (3-4 Hz) and further reduced to $\pm 0.3^{\circ}$ at 10 Hz. In addition to frequency-sweep also harmonic and pseudo-random excitation could be generated.

The instrumentation shown in the sketch, Fig. 7, was selected to get clear indication of the modes wing bending, store pitch and store yaw.

The structural responses of a full sweep sequence are given in Fig. 8. This mode preseparation by skilled pick up location is very important in respect to quick look and on-line analysis during the flutter test especially in case of close approach to the flutter boundary.

During the previously mentioned F-4 flight test also an excitation with binary pseudo random and harmonic signal was tried. In Fig. 9 the response data of the various kinds of excitation are compared. The resonance frequency for the harmonic excitation was defined from the on-line quicklook analysis and transmitted to the pilot for manual set-up during flight. Because of sharp resonance peaks and amplitude-dependent frequencies, it was very time consuming to reach the resonance condition. A promising improvement will be gained by use of an automatic excitation control loop described in chapter 6.

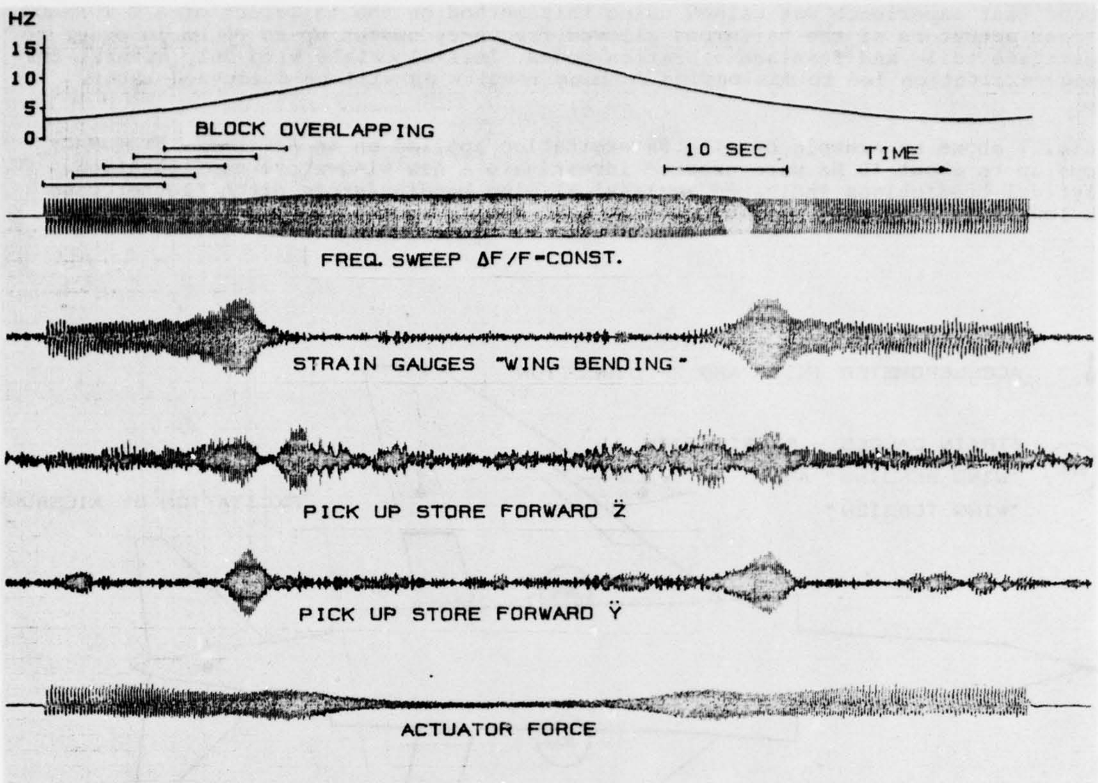

FIG. 8 RESPONSE TO FREQUENCY SWEEP EXCITATION FROM F-4F FLIGHT FLUTTER TEST

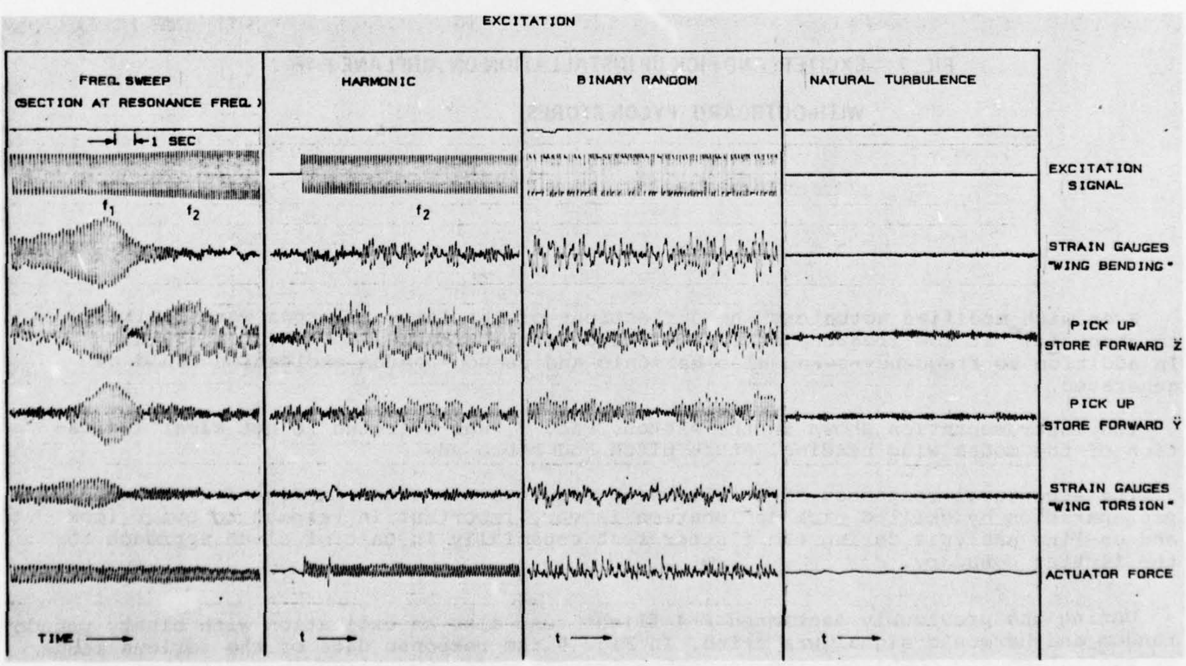

FIG. 9 STRUCTURAL RESPONSE TO DIFFERENT KINDS OF EXCITATION

3. DIGITAL TIME SERIES ANALYSIS

Modern digital computer capability led to a significant progress in digital analysis techniques.

High speed calculations with a great amount of data, implementation of statistical functions and steps to computer controlled data acquisition and processing opened new ways in performing tests. The use of "Fast Fourier Transform" (FFT) technique provided the basis for high speed computation in the frequency domain and easy conversion by means of FFT and inverse FFT.

3.1 Symbols and Relations

The following relations indicate the functions used in the analysis and how they are computed in the "Fourier Analyzer System".

x_t — time history of excitation

y_t — time history of structural response

$$\left.\begin{aligned} X_{i\omega} &= \mathfrak{F}(x_t) \\ Y_{i\omega} &= \mathfrak{F}(y_t) \end{aligned}\right\}$$ linear frequency spectra

$$\left.\begin{aligned} G_{xx} &= X_{i\omega} \cdot X^*_{i\omega} \\ G_{yy} &= Y_{i\omega} \cdot Y^*_{i\omega} \end{aligned}\right\}$$ autopower spectra
* indicates conjugate complex function

$$G_{yx} = Y_{i\omega} \cdot X^*_{i\omega}$$ cross power spectrum of structural response and excitation

$$H_{i\omega} = \frac{G_{yx}}{G_{xx}}$$ transfer function

$$h_\tau = \mathfrak{F}^{-1}(H_{i\omega})$$ impulse response function

$$\left.\begin{aligned} R_{xx} &= \mathfrak{F}^{-1}(G_{xx}) \\ R_{yy} &= \mathfrak{F}^{-1}(G_{yy}) \end{aligned}\right\}$$ autocorrelation functions

$$R_{yx} = \mathfrak{F}^{-1}(G_{yx})$$ cross correlation function

$$\gamma^2 = \frac{|G_{yx}|^2}{G_{xx}\, G_{yy}}$$ coherence function

where $\mathfrak{F}$ means the Fourier Transform and $\mathfrak{F}^{-1}$ the inverse Fourier Transform computed with FFT algorithm.

The equivalent relations between time- and frequency domain are illustrated in Fig. 10.

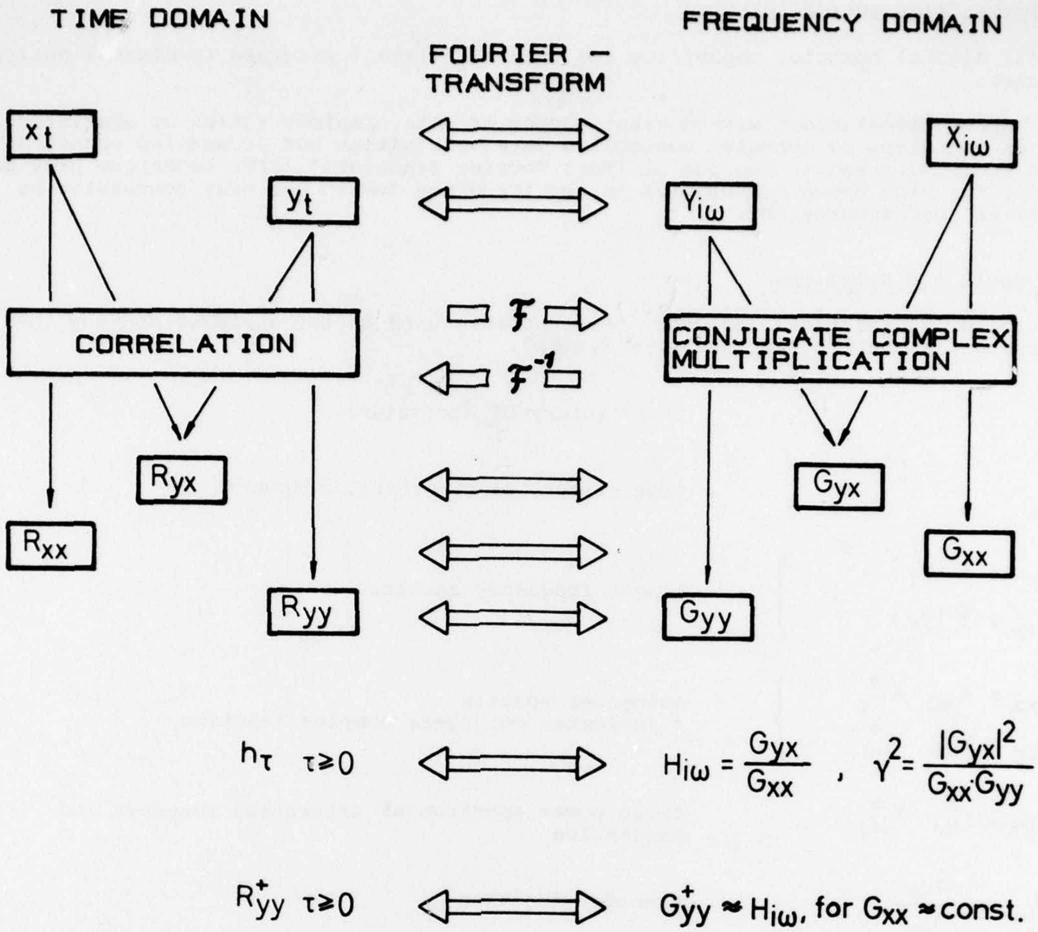

FIG. 10 RELATIONS IN TIME- AND FREQUENCY-DOMAIN

As shown in this figure there is a full equivalence of information in the relevant functions in time and frequency domain and an easy conversion via FFT.

The quick conjugate complex multiplication of Fourier converted time data blocks and reconversion to time domain is used on a Fourier Analyzer to get correlation- or cross correlation functions.

Considering the "direct" computation of a cross correlation function, which is

$$R_{yx}(\tau) = \frac{1}{T} \int_0^T x(t) \cdot y(t+\tau)\, dt$$

it can be recognized, that this requires a signal record length of $T+\tau$. Since the time data block only has the finite length T, the so-called wrap around error will be introduced. The computation of this function with variable integration interval

$$R_{yx}(\tau) = \frac{1}{T-\tau} \int_0^{T-\tau} x(t) \cdot y(t+\tau)\, dt$$

can avoid this error.

An equivalent computation, however, is not possible on the Fourier Analyzer, therefore other means of wrap around prevention have to be implemented as treated in chapter 3.3.

At MBB for flutter test analysis a Fourier Analyzer System HP 5451 B (Fig. 11) is used which consists of a digital computer with 32 K, disc storage, analog to digital converter (ADC), control- and display unit, keyboard, terminal, plotter and other in- and output devices. A standard program package "Fourier System" and "Modal Analysis" is available.

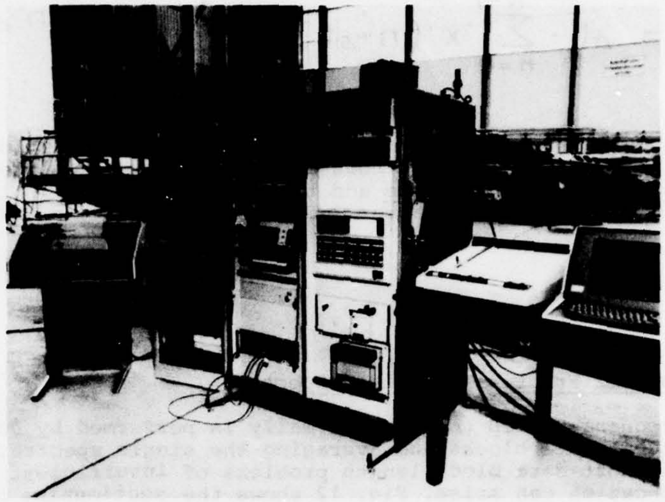

FIG. 11 MOBILE ANALYSIS EQUIPMENT

By simple keyboard programming the given subroutines can be connected to automatic running programs with predefined stops for display of results.

Also interaction with the test engineer at all program steps is provided, which is of importance in the described analysis technique.

The discrete finite data processing is based on the following parameters and relations:

N	blocksize (number of points in a data block)
Δt	sampling interval
$\frac{1}{\Delta t}$	sampling rate
$T = N \cdot \Delta t$	time-data block length
Δf	frequency resolution
$F_{max} = \frac{N}{2} \cdot \Delta f$	max. analysis frequency
$T = \frac{1}{\Delta f}$	important relation for selection of digital parameters, resulting from the above outlined formulas

To avoid aliasing error an adequate low pass filter must be used before analog-digital conversion ($f_{signal} \leq F_{max}$).

The infinite Fourier transform

$$X_{i\omega} = \int_{-\infty}^{\infty} x_t \; e^{-i\omega t} \, dt$$

is converted into

$$X'(m\cdot\Delta f) = \Delta t \cdot \sum_{n=0}^{N-1} x\,(n\cdot\Delta t)\cdot e^{-2\pi\cdot m\cdot\Delta f\cdot n\cdot\Delta t}$$

In the following the computation of power spectra and transfer function is described. For the mode separation in chapter 4 two methods are treated based on the transfer function: the "Filter correlation" technique and the "Modal analysis". Also treated are procedures to avoid wrap around error (chapter 3.3) and to smooth the transfer function (chapter 4.3).

3.2 Computation of Transfer Function and Power Spectra

The analysis of a frequency sweep test run normally is performed by computation of power spectra of subsequent data blocks and averaging the single spectra. Because of short test duration and short data block length problems of insufficient noise reduction and effects of truncation can arise. Fig. 12 shows the sectionning of a frequency sweep in single time data blocks and the averaged input power spectrum with clearly visible truncation effects.

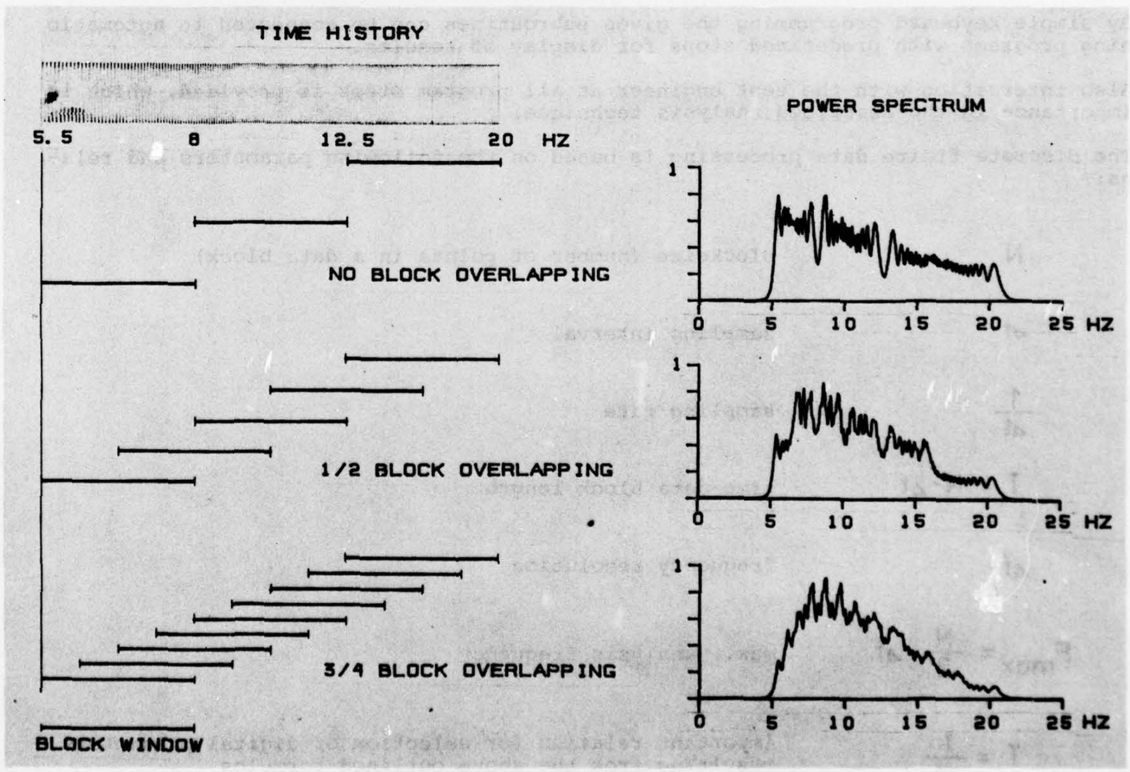

FIG. 12 ANALYSIS WITH OVERLAPPED TIME DATA BLOCKS

The block overlapping is a useful procedure to reduce truncation and noise effects as demonstrated in the successive calculations with 1/2 block- and 3/4 block overlapping. The amplitudes in the low and high frequency boundary are diminished by the averaging procedure of the overlapped data blocks (no influence to the transfer function).

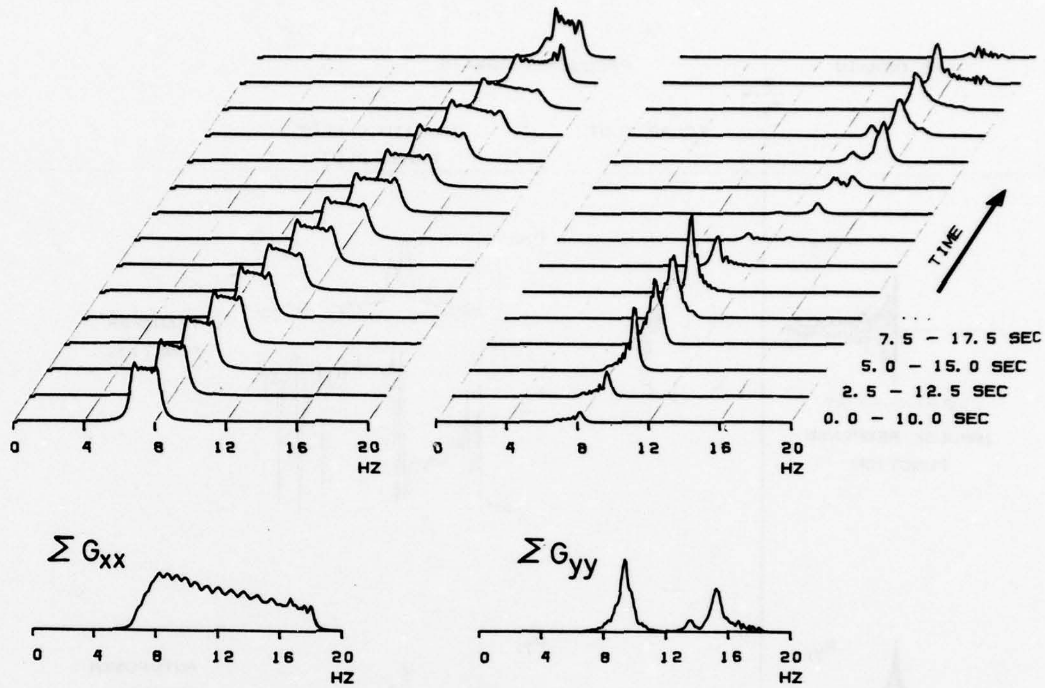

FIG. 13 AUTO-POWER SPECTRA DURING FREQUENCY SWEEP EXCITATION

Fig. 13 illustrates the time variable power spectra of input and system response during a frequency sweep with increasing frequency. These spectra are computed from 3/4 overlapped blocks. The result of the averaged single block calculations, given by :

$$\overline{G_n} = \frac{1}{n} \cdot \sum_{k=1}^{n} G_k$$

$\overline{G_n}$ averaged power spectrum from n single spectra

G_k power spectrum taken from single block computation

n number of averages

is plotted below the single block figures.

In these calculations with overlapped blocks data leakage must be avoided. The overlapped blocks are composed in computer storage either after recording the total sweep data on disc or during the blockwise read-in procedure.

From the averaged input and cross power spectrum the transfer function $H_{i\omega}$ is computed which represents the available complete composed system parameter description. The inverse FFT yields the impulse response function. These equivalent functions are the basis for the further mode separation. The computed coherence function γ^2 indicates the causal relationship between system input and output. In case of full relationship, γ^2 has the value 1, in case of no relationship 0. If only response data are available, an approximation of the transfer function can be tried. Therefore the one-sided autocorrelation function R^+_{yy} (the section of $-\tau$ is cleared) is taken as an approximation

of the impulse response function. Theory shows, that R^{+}_{yy} is proportional to the impulse response function in case of white noise input. It will be approximately proportional also in case of a partially constant input spectrum. The spectral function G^{+}_{yy} computed by Fourier conversion of R^{+}_{yy} is a complex function in which all modes have relative phase information (phase minimum system).

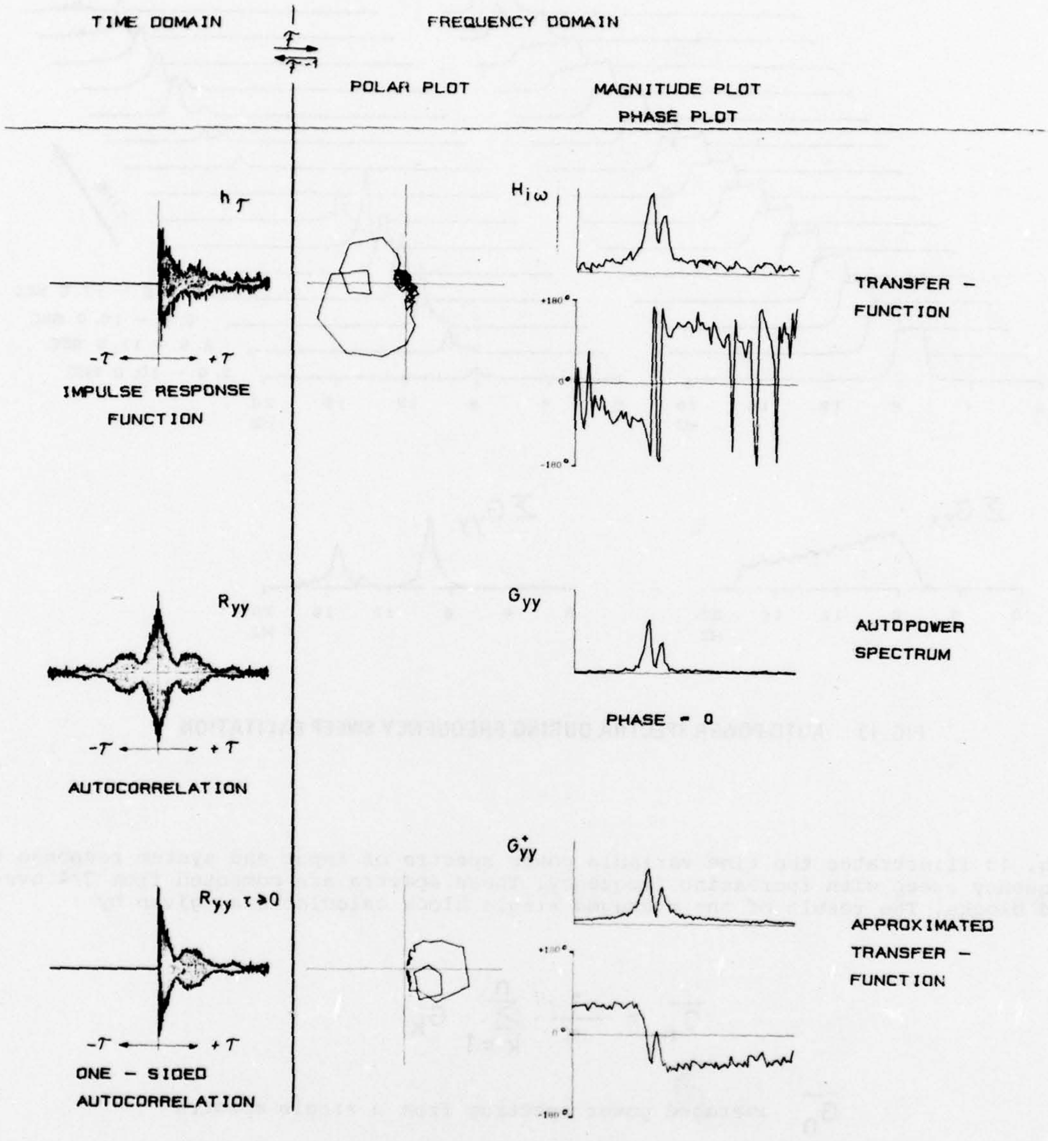

FIG. 14 EQUIVALENT FUNCTIONS IN TIME- AND FREQUENCY-DOMAIN

Fig. 14 presents equivalent functions in time- and frequency domain. On the top the impulse response and transfer function are shown computed from input- and response data. In the middle the autocorrelation function and autopower spectrum is plotted. The change to the one-sided autocorrelation function and approximated transfer function is plotted in the lower part of the picture.

3.3 Some Remarks to Calculation Errors

The calculated transfer functions or its approximations from output response data alone are taken to separate the modal parameters frequency and damping. Before these techniques are treated, attention should be drawn to possible calculation errors, which can appear in the finite digital analysis.

Fig. 15 gives a sketch of a time data block with the blocklength T (box car window) and its periodic repetition in the discrete finite transform (assumption of periodic function). On the right side of this figure the "wrapping" is displayed in another way. This causes an error, which is called wrap around error [18].

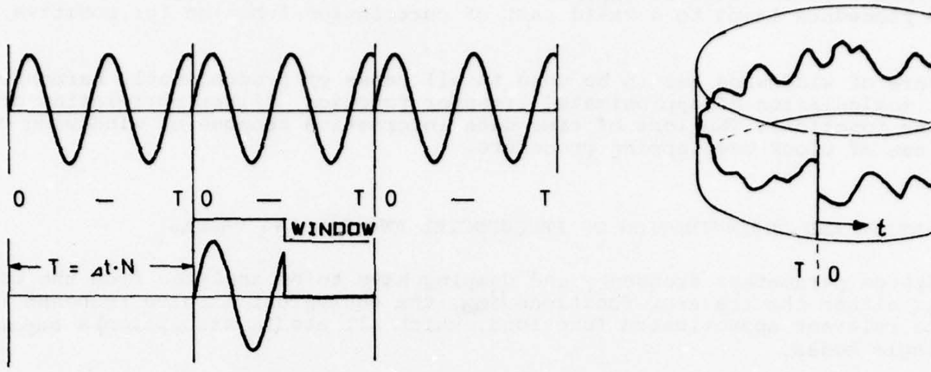

FIG. 15 TIME DATA BLOCK AND PERIODIC REPETITION IN FFT-CALCULATIONS

In case of signals with mainly periodic nature and in dependence on even or odd number of signal time periods in the box car window the wrap around error can be introduced as demonstrated in Fig. 16.

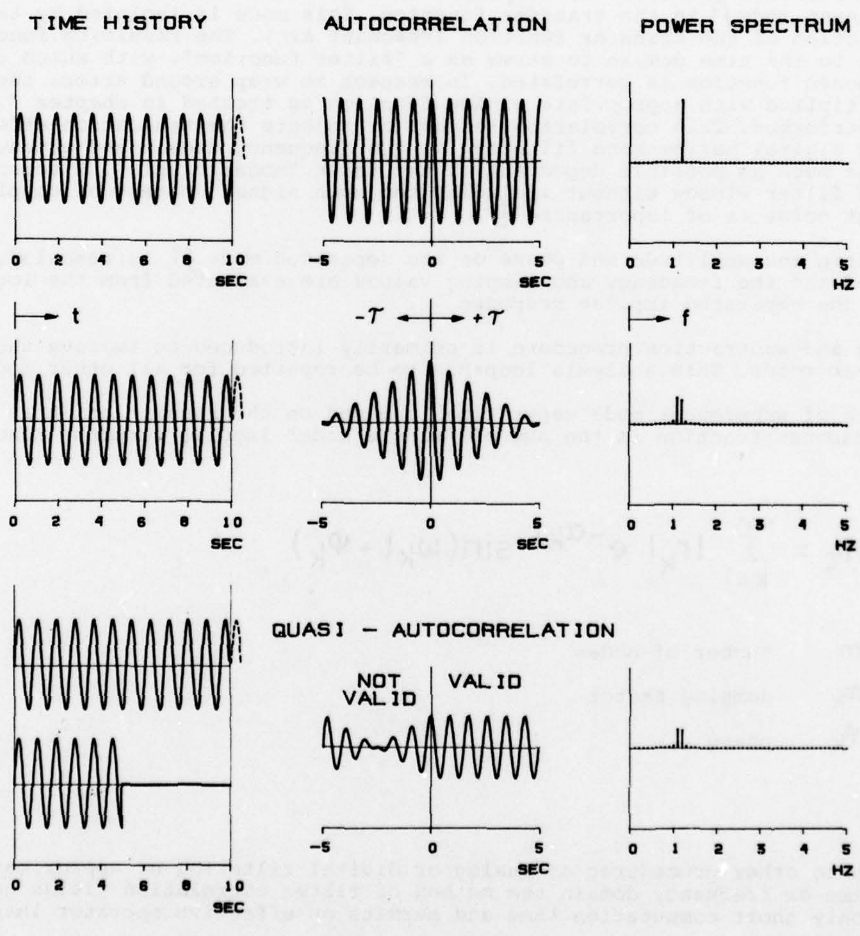

FIG. 16 ILLUSTRATION OF WRAP AROUND ERROR AND COUNTER MEASURE

The first case with an even number of periods in the box car window shows no data truncation, whereas in the next case with odd number of periods in the box car window a serious truncation of the autocorrelation function is created, leading to wrong damping values. The next step shows how this error can be eliminated by correlation of full data block against a block which is cleared in the second half (rectangular window). The result of this procedure leads to a valid part of correlation function for positive lag values τ.

This procedure of windowing has to be used in all cases of predominantly harmonic signal content (calculation of approximated transfer function, filter correlation of impulse response function). The loss of time data information because of windowing can be removed by use of block overlapping procedure.

4. MODE SEPARATION AND DETERMINATION OF FREQUENCIES AND DAMPING VALUES

The modal system parameters frequency and damping have to be analyzed from the computed functions either the transfer functions $H_{i\omega}$, the equivalent impulse response functions h_τ or the relevant approximated functions, which all are (by assumption) a superposition of single modes.

In principle many comparable ways of approximation techniques (to get an analytical system description) or filter techniques are possible. The differences as well as the method of solution are capability of noise rejection, calculation time, hard- and software requirements and possibilities for interaction during data evaluation.

In the following, two techniques are treated. One is the filter correlation technique (4.1) and the other is the modal analysis (4.2).

4.1 Mode Separation by Filter Correlation Technique

The filter correlation procedure is displayed in Fig. 17. It starts with the separation of the dominant mode $f1$ in the transfer function. This mode is isolated by taking a narrow band section of the transfer function (resonant arc). The resulting function is transformed back to the time domain to serve as a "filter function", with which the total impulse response function is correlated. In respect to wrap around error, the "filter function" is multiplied with appropriate window function as treated in chapter 3.3 before correlation is performed. This correlation reduces or rejects the truncation effects due to the foregoing digital narrow-band filtering in the frequency domain and attenuates also the noise as much as possible dependent on the taken "modal circle". A reasonable selection of the filter window without including too much signal content of coupled modes or adjacent noise is of importance [7].

In the next step the amplitude and phase of the separated mode $f1$ is rescaled, the result is plotted and the frequency and damping values are evaluated from the logarithmic plot of the separated impulse response .

The rescaling and subtraction procedure is primarily introduced to improve the separation of further modes. This analysis loop has to be repeated for all other modes.

This procedure of subsequent mode separation is based on the assumption, that the total impulse response function is the sum of "single mode" impulse response functions.

$$h_\tau = \sum_{k=1}^{m} |r_k| \, e^{-\alpha_k t} \sin(\omega_k t + \varphi_k)$$

m	number of modes
α_k	damping factor
φ_k	phase

In comparison to other procedures of analog or digital filtering or approximation procedures in time or frequency domain the method of filter correlation yields good results, needs only short computation time and permits an effective operator interaction.

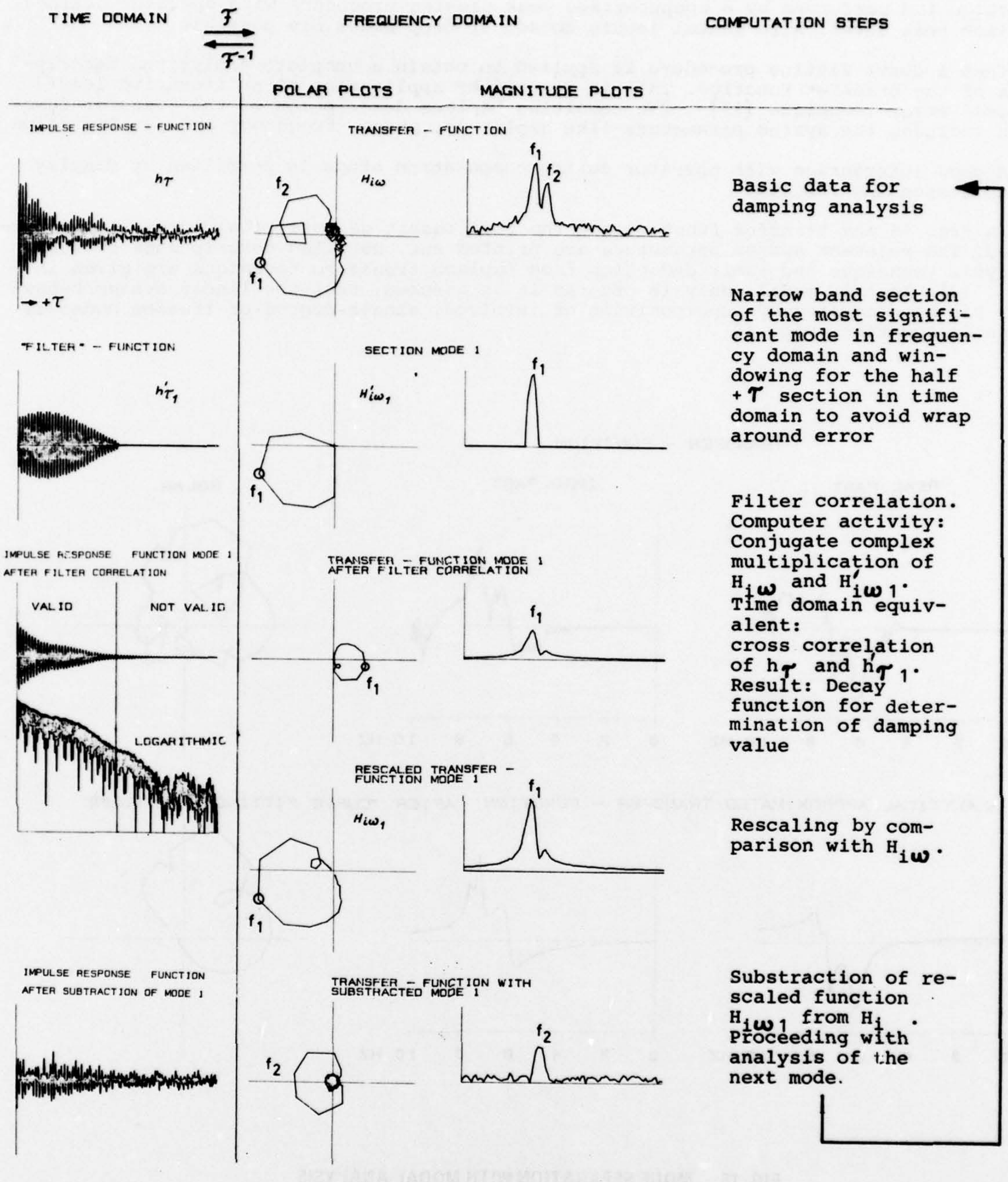

FIG. 17 MODE SEPARATION WITH FILTER CORRELATION TECHNIQUE

4.2 Mode Separation by "Modal Analysis" Technique

For the analysis of modal parameters a procedure called "modal analysis" is known and available as a program package for the Fourier Analyzer.

Basis for the frequency- and damping evaluation, here discussed, is the transfer function respectively impulse response function or approximated functions, which are computed as described in 3.2.

In the first stage of interaction with the operator, the number of smoothing operations has to be selected. This program step is equivalent to multiplication of impulse response function with an e-function. The introduced damping is subtracted in the result.

The next step is the mode identification based on the magnitude plot of transfer function and performed by a computerized peak picking procedure with operator defined minimum peak level. Also manual inputs to add or drop modes are possible.

Then a curve fitting procedure is applied to obtain a complete analytical description of the transfer function. This is reached by application of an iterative least squared error technique [13] . The resulting Laplace description of the transfer function includes the system parameters like amplitude, phase, frequency and damping value.

A good interaction with operator during computation steps is permitted by display of corresponding results.

In Fig. 18 the transfer function and the good result of analytical curve fit is compared. The relevant system parameters are printed out. Detailed descriptions of modal analysis technique and their deduction from Laplace transform technique are given in [12 , 13]. In this modal analysis program it is assumed, that the linear system behaviour can be described by superposition of involved, single-degree-of-freedom modes as shown in equation, page 15 .

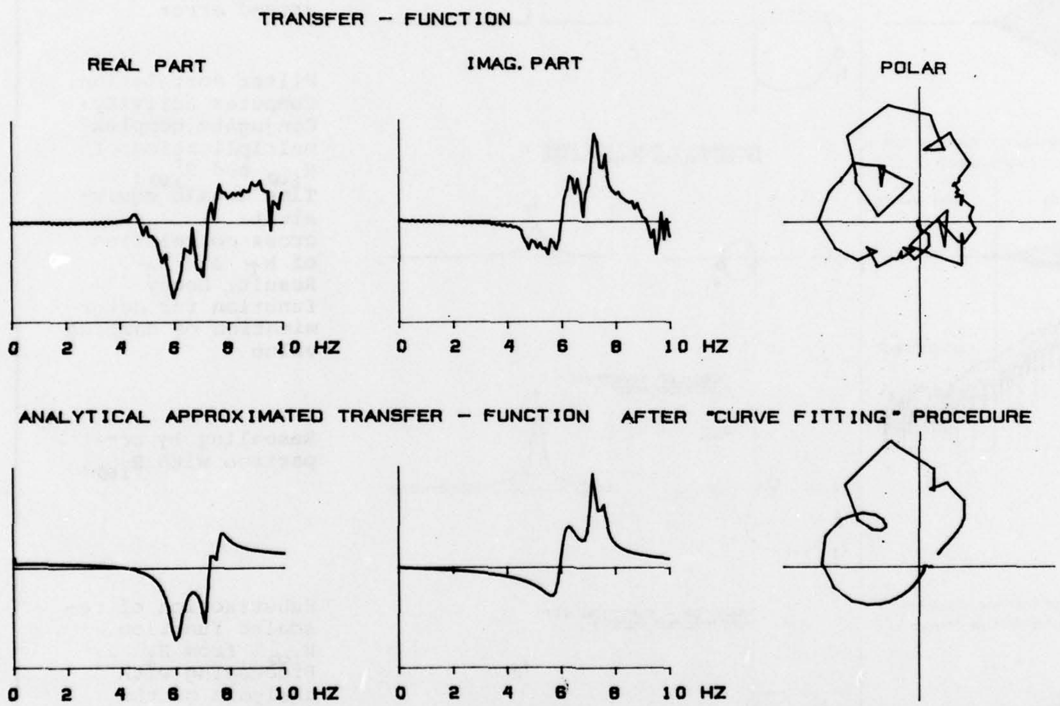

FIG. 18 MODE SEPARATION WITH MODAL ANALYSIS

4.3 Noise Reduction in Analysis

Many analysis-problems arise due to unknown excitation, nonstationary nature of flight environment and necessary restriction to short test duration. These limitations lead to a reduction in the statistical accuracy of transfer functions, computed from real flight test data.

Methods of averaging single block spectra in frequency domain and improvements by block overlapping procedure in order to reduce noise have been already mentioned. Autocorrelation or filter correlation with appropriate use of window function (as treated in 3.3/4.1) is another technique of noise reduction.

Frequently used methods of smoothing and windowing applied to the impulse response function are shown in Fig. 19.

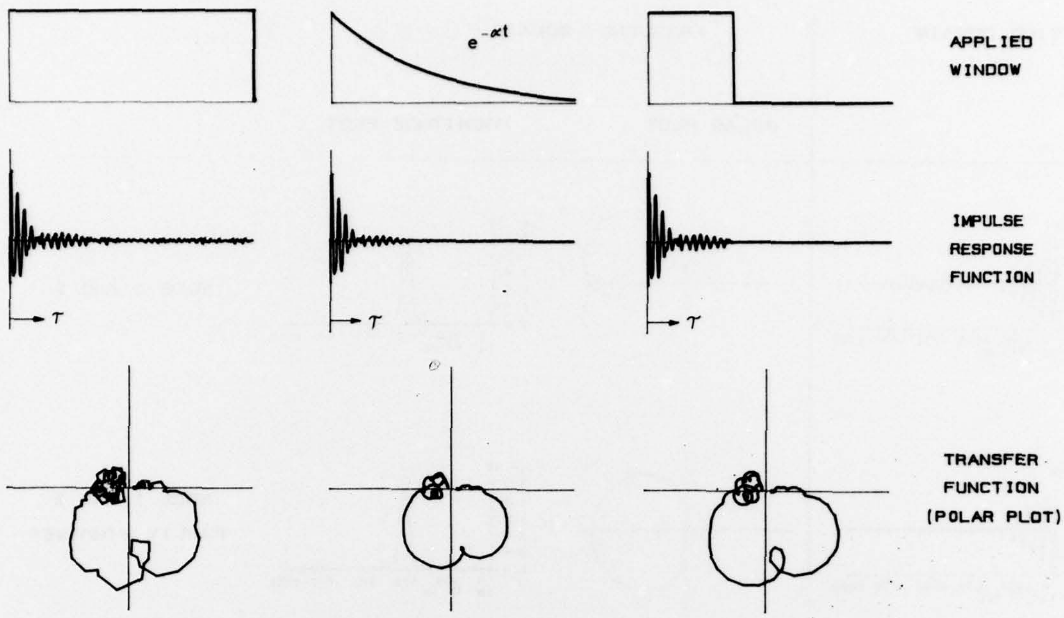

FIG. 19 APPLICATION OF WINDOW FUNCTIONS IN TIME DOMAIN

The multiplication with either exponential window or with rectangular window diminishes or disregards the rear part of the function. The ability of noise reduction by this smoothing method is based on the assumption of predominant noise content in the rear section.

In case of exponential windowing the system damping values are increased by a known value.

$$h'_{\tau} = \sum_{k=1}^{m} |r_k| \, e^{-(\alpha_k + \alpha)t} \sin(\omega_k t + \varphi_k)$$

symbols see page 15

α added damping factor

Therefore the correction in the analysis results is easy.

Proper application of a rectangular window function does not change the damping values.

However care has to be taken not to lose essential data information, which is e.g. necessary to separate closely spaced modes. Sometimes it is very difficult to decide from data in the time domain, which part of the function is dominated by noise and can be removed.

Analysis with artificially produced data with predefined system parameters is a helpful way to study the effects in application of these techniques.

Such an example is plotted in Fig. 20. Two closely spaced modes without any noise are taken to show the effects of unsuitable window function. Instead of two modes with low damping values only one mode with about twice the damping value will appear in the analysis. In case of superimposed noise the above mentioned difficulties selecting the window are indicated.

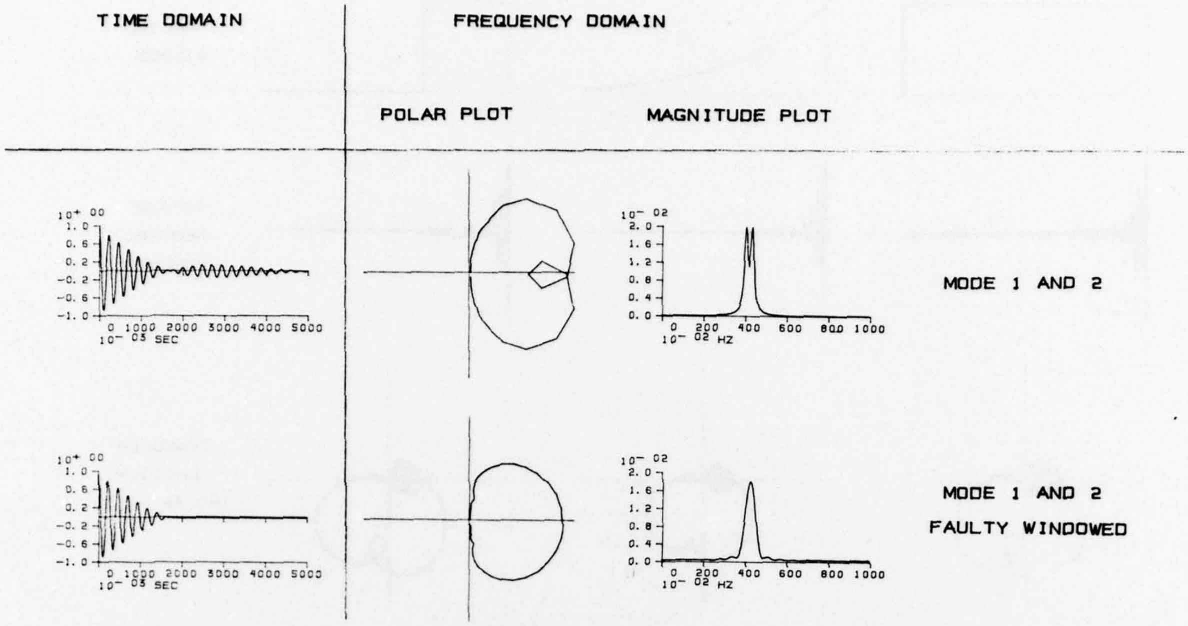

FIG. 20 ERROR CAUSED BY FAULTY WINDOWING

5. RESULTS OF APPLICATION IN FLIGHT FLUTTER TESTS

Some results from flight flutter tests concerning flutter investigations of wing store configurations and a taileron configuration are taken to point out some test results and problems and discuss test experience in application of the treated techniques.

Wing Store Configuration on a F-4F

Calculated and measured vibration modes as well as the flutter calculations were taken to define the test setup. In this case a classical wing bending - store pitch flutter mechanism with low flutter speed was predicted.

To excite the vibration modes of interest during the test, aileron excitation with frequency sweep excitation (log. sweep law) running from 3 Hz to 18 Hz and back to 3 Hz in duration of 80 sec. were used.

Excitation and pickup location is drawn in Fig. 7. Fig. 8 shows a frequency sweep run with measured system response. The mode separation by pickup location is clearly indicated in these figures. Results with frequency sweep-, harmonic-, pseudo random- and natural turbulence excitation have been illustrated in Fig. 9.

During the flutter tests a quicklook monitoring was performed based on

- time histories of response data (telemetered signals)
- computer controlled two channel analysis with subsequent prints of frequencies and damping values.

This was carried out at steady flight test conditions with frequency sweep excitation and with pseudo random excitation during acceleration to the next higher flight test point.

Further test parameters were symmetric and antisymmetric excitation, slats in and out and stability augmentation system on and off.

For the data evaluation a frequency resolution Δf = 0.1 Hz with the corresponding block time T = 10 sec. was choosen. The 3/4 block overlapping procedure allowed an average of 29 block-spectra in frequency domain. Also addition and subtraction of corresponding pickup signals was applied.

The results of extended postflight analysis are shown in Fig. 21. The analyzed frequencies and damping values and the extrapolated critical speed are in good correlation with the analytical prediction.

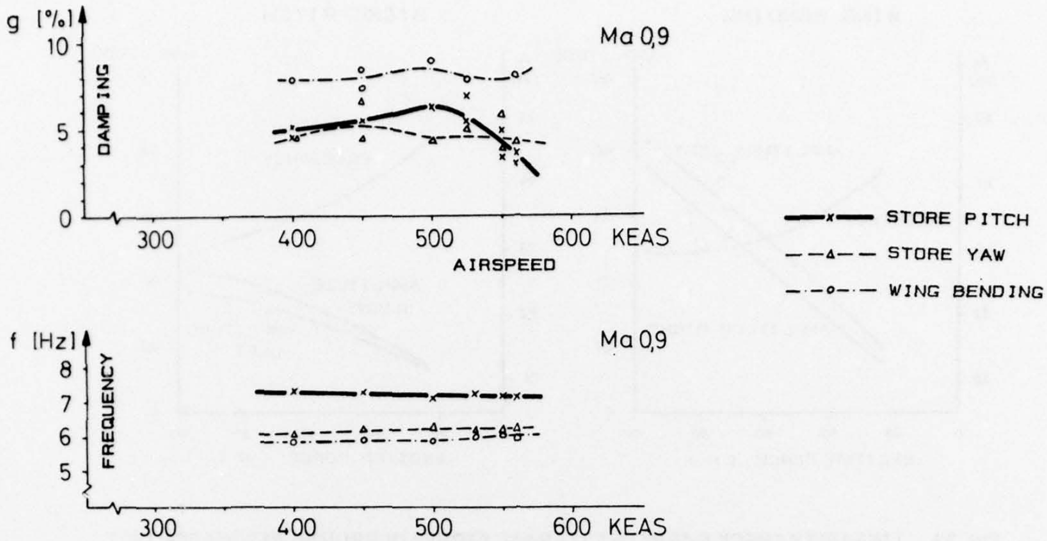

FIG. 21 DAMPING AND FREQUENCY PLOT FROM FLUTTER TESTS F-4F WITH EXTERNAL STORES

Fig. 22 and Fig. 23 indicate some complications due to asymmetries and mode coupling. On the left store the pitch mode with 7.1 Hz arised with less amplitude compared to the 7.2 Hz pitch mode on the right store. Similar frequency differences appeared in the wing *bending mode (5.8 Hz to 6.0 Hz) closely spaced and coupled to the store yaw mode (Fig. 22)*.

Linearity checks in preflight ground resonance test revealed some asymmetric and nonlinear structural behaviour (Fig. 23).

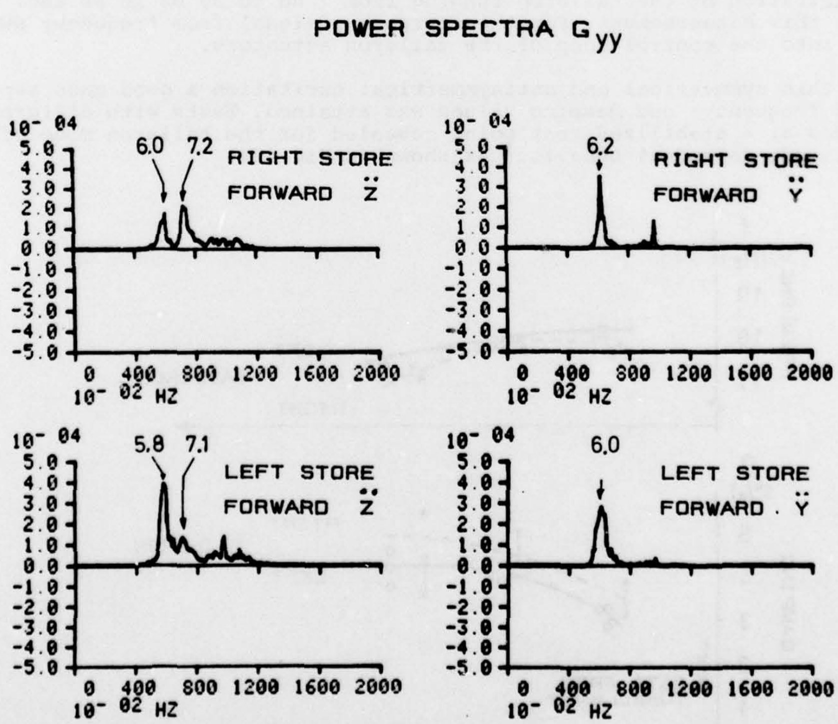

FIG. 22 ASYMMETRIES OF RIGHT AND LEFT STORE IN FLIGHT FLUTTER TEST

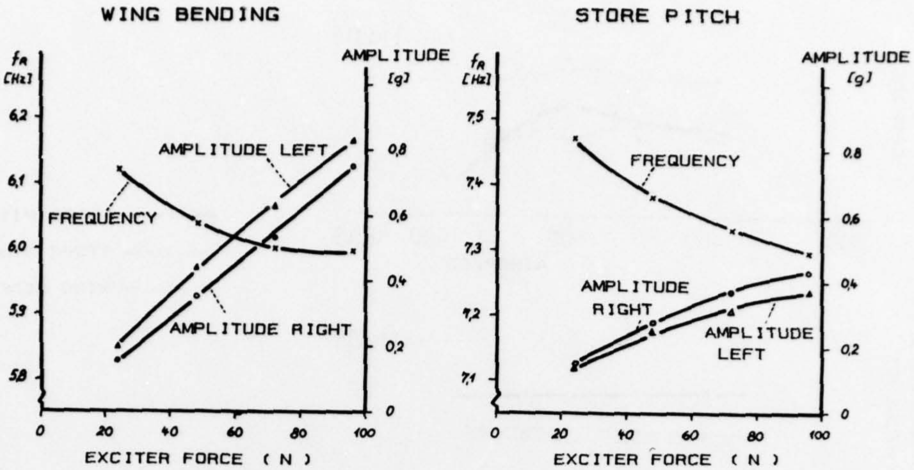

FIG. 23 LINEARITY CHECK F-4F WITH EXTERNAL STORES IN GROUND RESONANCE TEST

The close approach to flutter speed as to see in Fig. 21 requires a high quality of response data. As pointed out in this example an appropriate excitation and pick up location for preseparation of modes as well as suitable analysis technique is very essential in respect to a quick and safe test performance.

Flutter Monitoring of TORNADO-Taileron

The use of natural turbulence in flutter tests without artificial excitation is often propagated to simplify the test instrumentation. The intensity of natural excitation however is strongly dependent upon flight parameters and nonstationary flight environment. Some trials during flight envelope extension to monitor the flutter behaviour of the TORNADO taileron revealed lower damping values than predicted in calculation. Because of very small structural responses due to this natural excitation an additional frequency sweep excitation of the taileron running from 7 Hz to 30 Hz in 60 sec. was performed to clear this disagreement. For this purpose a signal from frequency sweep generator was fed into the control loop of the taileron actuators.

By means of this symmetrical and antisymmetrical excitation a good mode separation and analysis of frequency- and damping values was attained. Tests with different excitation amplitudes at a stabilized test point revealed for the taileron mode of interest a slightly amplitude dependent behaviour as shown in Fig. 24.

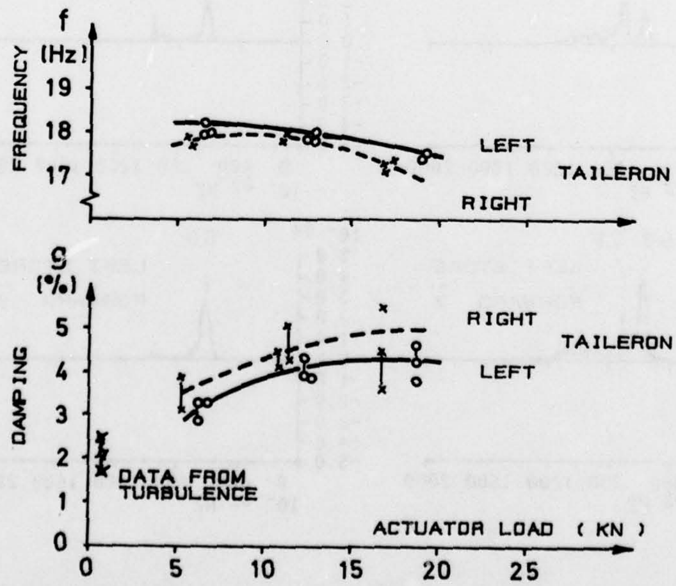

FIG. 24 NON-LINEAR AND ASYMMETRIC BEHAVIOUR IN TAILERON FLUTTER TEST

From this example it is indicated that non representative amplitude levels and insufficient signal to noise ratio can cause problems of test interpretation or misleading results due to effects of non-linearity.

6. QUICKLOOK ANALYSIS DURING FLIGHT FLUTTER TESTS

In wind tunnel and flight flutter tests there is a great interest in a fast test continuation. Quicklook analysis in addition to necessary extensive post flight analysis, is a great help in performing test.

Preseparation of vibration modes by means of selective excitation and pickup location is one of the necessary steps in this aim. Continuous quicklook of time histories gives monitoring information.

So-called Real Time equipment can be used for the purpose of continuous calculation and exponential average of correlation function and power spectrum. This is performed by subsequent data sampling and shifting through a shift register. Multichannel calculation in connection with the shift register during each sampling yields the desired functions. Compared with the blockwise computation on the Fourier Analyzer there is an advantage in averaging and subsequent data display. The limited number of store-registers and difficulties in further data processing e.g. mode separation restrict the application.

Therefore a quicklook computer program was developed and tested based on the analysis methods described here (see section 3 and 4) and application of the Fourier Analyzer.

The flow diagram is shown in Fig. 25. In parallel to the sampling of a new time data block the analysis is performed from the last time data blocks. The exponentially average is computed according to

$$\overline{G}_n = \left(1 - \frac{1}{p}\right) \cdot \overline{G}_{n-1} + \frac{1}{p} \cdot G$$

$\overline{G}$ exponentially averaged power spectrum

G new power spectrum (of a single time data block)

p weighting factor ($p > 1$)

The choice of the weighting factor allows an appropriate adaption of averaging to a given case.

The automatic filter correlation is performed for modes of interest defined by preselected frequency bands. The resulting frequency- and damping values are subsequently printed out. Random excited responses can be analyzed in the described way, in case of frequency sweep excited responses a linear averaging of full sweep period is required before analysis is performed. Further improvements in this quicklook analysis are expected by use of transfer function technique.

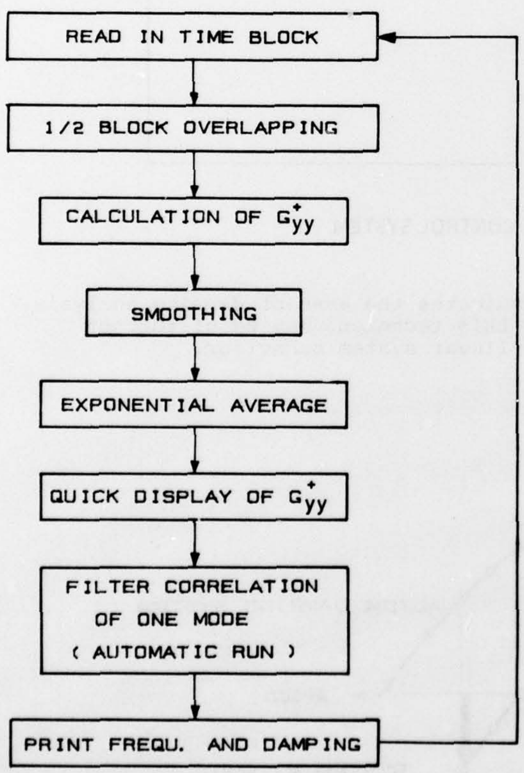

FIG. 25 FLOW DIAGRAM OF QUICKLOOK ANALYSIS

7. AUTOMATIC EXCITATION AND DAMPING

A logical step forward in the application of aerodynamic vanes and control surfaces to produce suitable aircraft excitation was the implementation of a control loop to introduce automatic damping, and for special test purpose automatic mode excitation. Interesting results of application in wind tunnel flutter model tests were presented in [5], successful tests with an aircraft G 91 with wing stores showed the effectiveness of these techniques [6].

Fig. 26 gives a sketch of selected sensors, the control loop and the vane actuation of a flutter model in order to test a store pitch mode with suitable sensor selection and appropriate gain in the control loop. The system automatically tunes the frequency into selected modes. Compared to very time consuming manually frequency search to reach the resonance frequency, this automatic excitation system provides promising test application especially to wing store configurations.

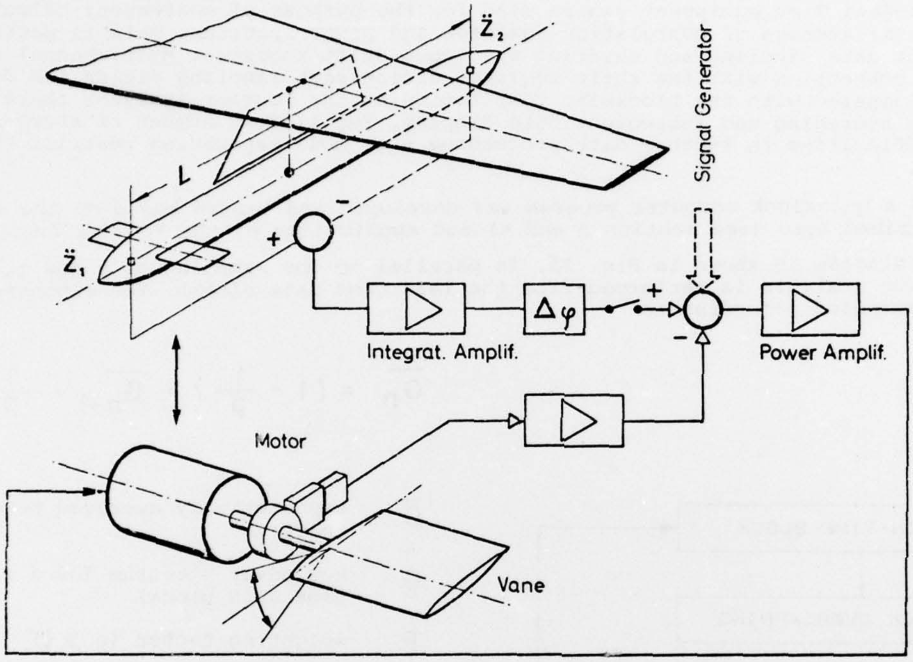

FIG. 26 BLOCK DIAGRAM OF VANE CONTROL SYSTEM

Fig. 27 shows the results of application and indicates the ease of damping analysis. More details are given in [5 , 6]. Application of this technique may be of further advantage in the investigation of significant non-linear system behaviour.

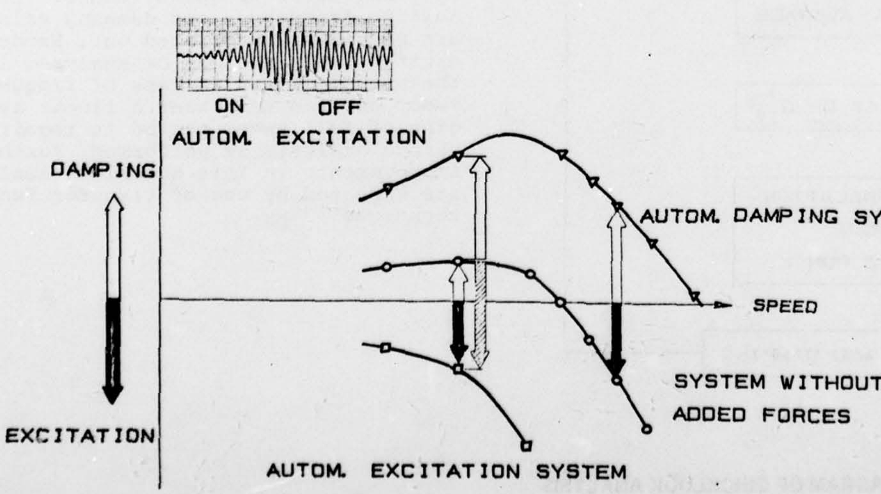

FIG. 27 RESULTS OF AUTOMATIC EXCITATION AND DAMPING-TECHNIQUE

8. CONCLUDING REMARKS

In the application of the described excitation- and analysis technique together with the mentioned equipment good test experience has been gained. The illustrated analysis-smoothing- or other data manipulation-techniques permit optimal use of real "system information" contained in the response data, however they cannot replace the need for adequate response data.

Therefore a reasonable aircraft excitation and instrumentation is very important in order to fulfill this task.

In case of slightly non-linear system behaviour different excitation-levels and selective excitation is helpful to define representative system parameters and to avoid misleading results.

Care has to be taken in case of strong non-linearities. Corresponding investigations are treated in Ref. [19].

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REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-R-672	ISBN 92-835-1309-6	UNCLASSIFIED

5. Originator	Advisory Group for Aerospace Research and Development North Atlantic Treaty Organization 7 rue Ancelle, 92200 Neuilly sur Seine, France
6. Title	EXCITATION AND ANALYSIS TECHNIQUE FOR FLIGHT FLUTTER TESTS
7. Presented at	the 47th Structures and Materials Panel Meeting, Florence, Italy, September 1978.

8. Author(s)	9. Date
G.Haidl and M.Steininger	January 1979

10. Author's Address	11. Pages
Messerschmitt-Bölkow-Blohm GmbH. Unternehmensbereich Flugzeuge Postfach 80 11 60, 8 München 80	30

12. Distribution Statement	This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Flutter	Excitation	Flight tests
Aeroelasticity	Resonant frequency	Aerodynamic forces
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14. Abstract

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The second part of the paper deals with the digital analysis of flight flutter test data. Recommendations for selection of analysis parameters and how to avoid errors due to digital processing are given. For data evaluation in flight flutter tests the autopower-spectrum and transfer- and coherence function are used. Errors and effects of digital blockwise computation and analysis procedures like block overlapping, windowing, averaging or curve fitting are demonstrated.

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ISBN 92-835-1309-6